Long Distance Telephone Circuits in Cable *

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This paper first very briefly reviews the history of long distance telephone cables in the United States. A statement is then given of the basis of the electrical design of present day cables, followed by a discussion of the standards applied to cable circuits and the application of cables to the telephone needs of the country. While the present system is satisfactory for the circuits now used in cable up to distances of 1800 miles (3000 kilometers) or more, it would not be satisfactory for the much greater distances expected for the future, both for continental and intercontinental service. The paper closes with a brief account of the progress which has been made in the development of a cable carrier telephone system which is expected to be satisfactory for any distances which may in the future be spanned by telephone circuits in cable.

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DURING the last two decades there has been, in all countries which have a large telephone development, a remarkable increase in the use of long distance telephone circuits in cable resulting in the building up of such large networks of long distance telephone cables as those which today cover the continent of Europe and a part of the continent of North America. This paper discusses the technical problems encountered in this development and the solutions applied in the development of the long distance cable network of the United States of America, using this as an illustration because it is the telephone plant with which the authors are most familiar.

Important Cable Development Milestones in the United States

The early long distance telephone circuits in the United States were practically all open wire. In fact, great care was exercised in laying out open-wire circuits to eliminate the necessity for using even short stretches of cable. Cable began to be considered seriously for long distance service when loading became available. In 1902 the first commercially loaded cable circuits in the United States were installed between New York City and Newark, N. J., a distance of about 11 miles (17 kilometers). Other cables rapidly followed, until in 1906 loaded cables were installed between New York and New

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Haven, a distance of 79 miles (127 kilometers), and between New York and Philadelphia, a distance of 87 miles (140 kilometers). These 1906 cables contained No. 14 A. W. G. conductors (1.6 millimeters in diameter) and were loaded with 250-millihenry inductance coils spaced about 6000 feet (1830 meters) apart. By means of these cables it was possible to obtain transmission equivalents low enough so that these circuits furnished what was then considered very good long distance service. These early cables consisted entirely of physical circuits.

In order to obtain more circuits from the same number of wires, much development effort was then spent on methods for phantoming cable circuits and loading the phantoms. A number of problems were encountered and solved, the most serious being the problem of avoiding undue crosstalk between the circuits due to fortuitous unbalances introduced at the loading points and between the cable conductors. The problem was finally solved and in 1910 a short cable was installed between Boston and Neponset, Mass., providing loaded phantom circuits as well as side circuits, thus increasing the number of circuits 50 per cent. This was followed by a rapid extension of the use of this type of cable.

The ultimate in large gauge loaded cables was achieved in 1914 when the installation was completed of underground cable from Boston to Washington, a distance of 450 miles (724 kilometers), New York City being about at the midpoint. Some of the conductors in the cables were No. 10 A. W. G. (2.6 millimeters in diameter) while others were No. 13 A. W. G. (1.8 millimeters in diameter). Most of the loading consisted of 200-millihenry coils on the sides and 135-millihenry coils on the phantoms, spaced 7400 feet (2255 meters) apart. The 1000-cycle losses per mile (per kilometer) on these circuits were .050 (.031) db for the sides and .040 (.025) db for the phantoms for No. 10 A. W. G. and .085 (.053) db and .070 (.043) db for the side and phantom, respectively, of No. 13 A. W. G.

The vacuum tube telephone repeater was demonstrated as a great success when the New York-San Francisco telephone line was officially opened January 25, 1915. When this device was applied to the then available loaded cable circuits various imperfections, unimportant on non-repeatered circuits, produced serious effects, some of which had already been encountered in the work leading up to the loading of the open wire transcontinental line. Among these were the impedance characteristics of the cable circuits which were irregular due in part to insufficient stability and uniformity in the capacitances of the individual loading sections. These impedance irregularities prevented

good repeater balances being obtained and consequently restricted the amplification which could be utilized on two-wire circuits.

It was soon realized that even if the loading were made very uniform two-wire repeatered circuits would be restricted in their transmission ranges, partly because of the unbalances encountered at repeaters and partly because of the tendency of the circuits to crosstalk into each other. Experiments were therefore begun utilizing the four-wire circuit method. When four-wire circuits were first set up using the large gauge loaded circuits between Boston and Washington great difficulty was experienced in obtaining even reasonably uniform attenuation at different frequencies. It then became apparent that smoother (more uniform) circuits would be necessary. It also became evident that higher cutoff frequency and higher velocity loading was necessary, in order to widen the effective transmission band and reduce delay distortion and echo effects. As a first step in this direction a system of loading in which inductance coils of 175 millihenries on the side circuits, spaced 6000 feet (1830 meters) apart, was introduced, primarily for two-wire circuits. This was commonly referred to as medium-heavy loading, having a cutoff frequency of approximately 2800 cycles. Experiments on long four-wire circuits with this loading which were specially set up for test confirmed the previous ideas as to the seriousness of echo effects and delay distorton effects and made it apparent that a much lighter weight and higher cutoff loading would be necessary for great distances. Accordingly, a system of loading known as H-44-25 (6000 feet—1830 meters—spacing with 44-millihenry coils on the sides and 25-millihenry coils on the phantoms) was introduced. This was the beginning of modern long distance cable circuits in America.

Electrical Design of Toll Cable Circuits

It is impracticable in a short paper such as this to deal fully with all of the considerations which determine the electrical design of cable circuits. There are set down here, however, the important characteristics of the types of circuit which have been adopted for use in the United States and the reasons why certain arrangements were selected. Many specific designs which will meet the transmission objectives are, of course, possible. The designs selected have been based upon the aim of obtaining the desired results in the most economical manner, including the advantage which comes from concentrating on a small number of types of circuits, rather than on a larger number designed to meet accurately the requirements of different types of situations. In other countries where the ratios of costs for different parts of cable

systems are different it is to be expected that the most economical designs will differ.

Cable Constants

The toll cable which is standard in the Bell System plant has capacitance of .062 microfarad per mile (.038 mf. per km.) for the side circuits and about .100 microfarad per mile (.062 mf. per km.) for the phantoms. There appears to be little to gain for voice-frequency circuits by varying materially from these capacitance figures.

With respect to size of wire, No. 19 A. W. G. conductors (.9-millimeter diameter) are well suited for both two-wire and four-wire circuit operation. No. 16 A. W. G. conductors (1.3-millimeter diameter) have been employed to a considerable extent in the past. In new cables conductors of this gauge are, in general, used only for relatively short non-repeatered circuits, or for program circuits. At the present time the possible economic advantage of using smaller sizes of wire than No. 19 A. W. G. is so small that it is considered to be outweighed, in general, by the greater complexity and variability of the circuits which would result.

Side Circuits and Phantoms

With the exception of program transmission circuits, multiple twin quads, utilizing both the side and phantom circuits, are used exclusively.

The ratio between the capacitances of phantoms and side circuits is about 1.6, while the ratio of resistances is 0.5. Because of this the phantoms which are loaded for the same cutoff frequency as the side circuits have lower attenuation and lower impedance than the side circuits. For repeatered circuits the phantoms and sides are so operated that they give substantially equal transmission results, this being desirable for flexibility reasons.

Two-Wire and Four-Wire Circuits

As is well known, two-wire repeatered circuits are more economical for the shorter distances while four-wire circuits are necessary to economically provide satisfactory transmission for longer distances. It is possible for terminating business to design two-wire cable circuits which will deliver good telephone service for distances of at least 900 miles (about 1500 kilometers). However, to meet the transmission standards current in the United States four-wire circuits are generally more practicable for distances more than two or three hundred miles (a few hundred kilometers).

Inductance and Spacing of Loading Coils

Theoretically the inductance and spacing of loading coils might be varied for each circuit length in order to obtain the most economical design. Studies which have been made, however, indicate that, taking into account the advantage of flexibility, it is desirable to use only two types of spacings of loading coils and only two general types of loading units. In the Bell System the toll loading coil spacings are 3000 feet (915 meters) and 6000 feet (1830 meters), loading with these spacings being designated B and H, respectively. For two-wire circuits, 88-millihenry loading coils for the sides and 50-millihenry coils for the phantoms are used with both spacings, giving loadings designated as B-88-50 and H-88-50. The choice between these is dictated by the repeater spacing. If less than about 45 miles (72 kilometers), H-88-50 loading is used; if greater, B-88-50 is used. Two-wire H-172-63 loading was used in the past for two-wire circuits but this has now been given up for new work in favor of the wider frequency band B and H-88-50 systems.

For four-wire circuits, as stated above, the standard loading is H-44-25 meaning, of course, 6000-foot (1830-meter) spacing of coils with 44-millihenry coils on the sides and 25-millihenry coils on the phantoms.

Important Transmission Characteristics of Loaded Cable Conductors

The characteristics of loaded cable circuits depend principally upon the electrical constants of the cable conductors, the inductance of the loading coils and their spacing. Some of the more important transmission characteristics of the loaded cable systems employing cables and loading coils of the type just described are given in Table I.

Spacing of Repeaters and Automatic Transmission Regulators

Repeaters are spaced as close to 50 miles (80 kilometers) apart as practicable. In the past variations upward from this to about 60 miles (100 kilometers) were allowed but it is now believed best to avoid such long spacings. Where the location of cities or other geographical situations make it desirable, spacings less than 50 miles (80 kilometers) are used.

Automatic transmission regulators are provided for circuits in aerial cables in excess of 50 to 100 miles (80 to 160 kilometers) in length and are preferably placed at every second repeater station. The devices are such, however, that satisfactory results may be obtained if regulators are as far apart as about 150 miles (250 kilometers), while under certain conditions circuit flexibility considerations call for regulators at adjacent repeater stations. With cable entirely

underground transmission regulators will function satisfactorily from the electrical standpoint spaced as far apart as 300 miles (500 kilometers) although circuit flexibility considerations usually call for breaking circuits up into shorter regulator sections. In general, regulators are provided for all circuits in underground cable in excess of approximately 180 miles (300 kilometers) in length.

TABLE I

CHARACTERISTICS OF 19-GAUGE REPEATERED TOLL CABLE CIRCUITS

	Two Wire				Four Wire 11-44-25	
	B-88-50		H-88-50			
	Side	Phantom	Side	Phantom	Side	Phantom
Characteristic Impedance—Ohms at 1000 Cycles	1,560	930	1,120	670	800	450
Attenuation at 1000 Cycles						
db Per Kilometer at 55° F.	.17	.15	.22	.19	.30	.25
db Per Mile at 55° F.	.28	.23	.35	.30	.47	.39
Nominal Velocity—						
Kilometers Per Second	16,000	17,000	23,000	24,000	31,500	33,000
Miles Per Second	10,000	10,500	14,300	15,000	19,000	20,000
Cutoff Frequency of Loading—Cycles Per Second	5,600	5,900	4,000	4,200	5,600	5,900
Attenuation Change at 1000 Cycles—						
db Per Kilometer						
Aerial (55°–109° F.)	.019	.016	.025	.022	.034	.029
Underground (55°–73° F.)	.007	.006	.009	.007	.011	.010
db Per Mile						
Aerial (55°–109° F.)	.031	.026	.041	.035	.055	.046
Underground (55°–73° F.)	.011	.009	.014	.012	.018	.015

Gains of Repeaters

In four-wire circuits the spacing of the repeaters and their gains depends largely on "one-way circuit" considerations. The maximum levels are fixed by the repeater and loading coil capacities to handle speech waves without distortion, the lower levels being fixed primarily by noise. The lower levels also depend somewhat on crosstalk considerations, particularly crosstalk between circuits transmitting in opposite directions but this crosstalk is usually not controlling. The upper level limit used is + 10 db while the lower is − 24 db, these being referred to the level at the transmitting end of the toll circuit as zero.

In two-wire circuits, the above "one-way circuit" considerations are unimportant in determining the levels, these being largely fixed

by "two-way" considerations. The important "two-way" considerations are crosstalk on the one hand and proper control of circulating currents which might cause singing or serious echoes on the other hand. These considerations keep the repeater gains so low that the limit of repeater and loading coil capacity is not important nor is the lower limit at which noise would become serious.

The most important crosstalk consideration on two-wire circuits is "near-end" crosstalk. The arrangement of repeater gains which gives lowest near-end crosstalk is one in which the output levels of the repeaters are the same throughout the circuit until the receiving end is reached, at which point the repeater gain is reduced or loss inserted as necessary to give the desired overall net loss for the circuit.

This arrangement is not best from the standpoint of the circulating currents, however. From this standpoint the best setup is one in which the repeater output levels "taper" considerably from the sending end to the receiving end of the circuit.

In the Bell System plant a compromise is made between these two considerations which calls for layout of gains about as follows: At the transmitting end the transmitting repeater gain is made such that the outgoing level is + 3 db. As the transmission passes through other repeaters the upper level is allowed to drop about ½ db per repeater for average temperature conditions. Finally at the receiving end of the circuit gain or loss is introduced to give the required net loss for the circuit. Of course, the application of the above rules for laying out repeater gains results in giving individual repeaters different gains in the two directions.

Smoothness of Impedance

For two-wire circuits it is important that the cables have a "smooth" impedance-frequency characteristic. To attain this result, loading coil inductances are held within close manufacturing tolerances while the cable capacitance variations are also carefully controlled. In the field care is, of course, taken with the spacing of the loading coils. Following are some representative figures for side circuits of fractional deviation from the average values per loading section or per loading coil:

	H Spacing	B Spacing
Representative deviation of cable capacitance *	.013	.018
Representative deviation of loading coil spacing *	.005	.005
Representative deviation of loading coil inductance *	.007	.007
Total deviation	.016	.020

* Representative deviation is the square root of the mean square of the individual deviations.

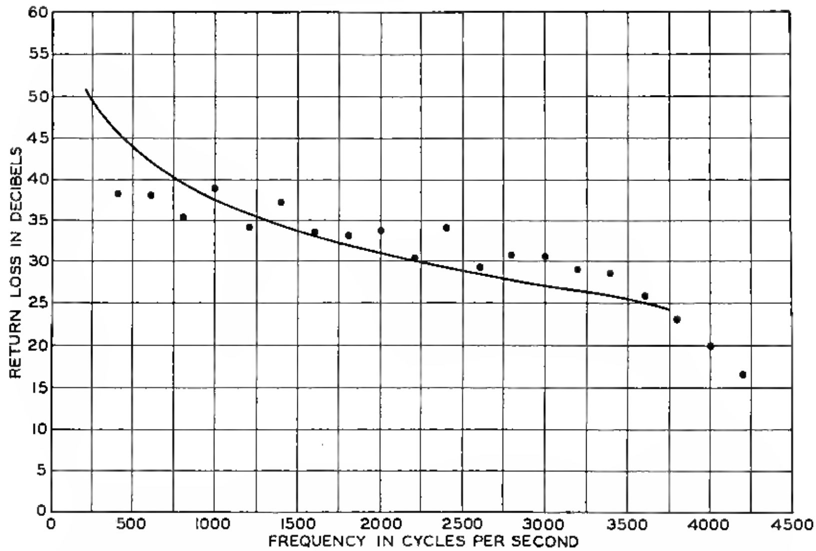

Fig. 1—Representative return losses on 19-ga. B-88-50 side circuits. 37 per cent of the measurements show lower return losses. ● 26 circuits Newark to Princeton.

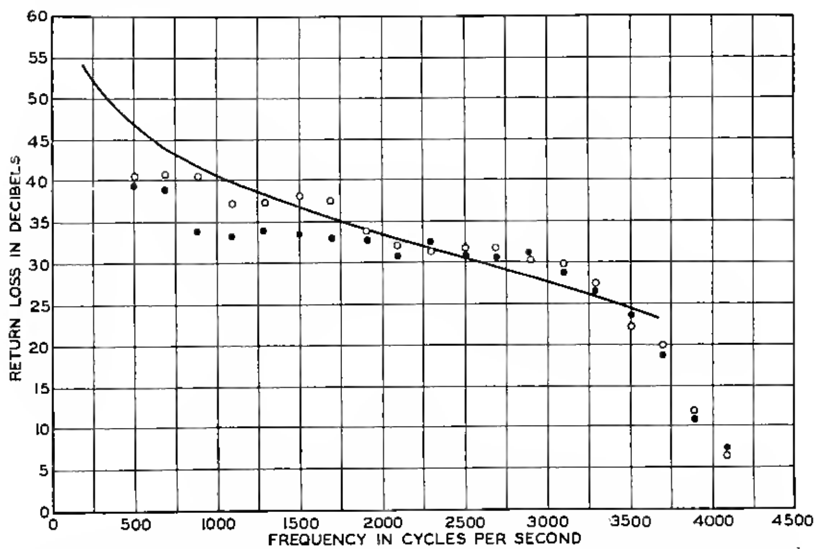

Fig. 2—Representative return losses on 19-ga. H-88-50 side circuits. 37 per cent of the measurements show lower return losses. o 26 circuits Princeton to Newark. ● 26 circuits Princeton to Philadelphia.

Representative return loss versus frequency curves are shown in Figs. 1 and 2 for B-88-50 and H-88-50 circuits, respectively, the points plotted being corresponding measurements on actual field facilities.

In the case of four-wire circuits, impedance irregularities are not so serious. However, for practical reasons, the same tolerances are usually followed for the several parts.

Control of Crosstalk

For two-wire circuits, the important crosstalk is near-end while for four-wire circuits it is far-end. For both of these, crosstalk between circuits within a single quad is greatest but crosstalk between circuits in different quads is also important. For two-wire circuits, in order to avoid long crosstalk exposures between any two circuits, it is the practice to carry three circuits together in a single quad only in a single repeater section, the circuits being systematically mixed at each repeater station. In the case of four-wire circuits this mixing is done only at the ends of regulator sections. In both outside cables and in the office cable, care is exercised to segregate the oppositely bound pairs of four-wire circuits because of the relatively large level differences.

In the outside cables control of crosstalk involves adjustments of the fortuitous unbalances in the loading units and unbalances between circuits in the loading sections. The following table shows the standards for phantom-to-side crosstalk expressed in decibels ordinarily worked to for the component parts of cable circuits:

	Two-Wire				Four-Wire	
	B-88		H-88		H-44-25	
	Avg.	Max.	Avg.	Max.	Avg.	Max.
Repeater section outside plant*	78		82		76	
Loading coil	96		96		96	
Cable proper per load section	93		94		94	
Toll office*	79		82		80	
Office wiring	80		86		82	
Office equipment	86		84		84	
Repeaters		91		91		74

* For two-wire circuits on the average these values must be decreased about 8 db to compare with overall value; for four-wire circuits about 9 db should be added to these values to compare with the overall.

Note: All values in table are for a frequency of 1250 cycles.

Control of Delay Distortion

In the case of two-wire circuits, since only relatively short distances are involved, delay distortion does not enter as a design factor. In the case of long four-wire circuits delay distortion is very important and to avoid this, very light weight and high cutoff loadings are used. Delay distortion may be reduced by employing correcting networks which introduce distortion counter to that introduced by the line. Such networks, in addition to their cost, have the disadvantage that they increase the total delay of the circuit. Their use is not necessary for the lengths of circuits and types of construction now used for message telephone circuits in the United States.

Performance Characteristics

Minimum Working Net Loss

In determining the numbers of circuits of different types of construction to be provided in a proposed cable for long distance work, it is necessary to take into account the limiting lengths for which the different types of circuit will meet the transmission requirements established for different conditions. This limitation for repeatered circuits is not set by attenuation but rather by singing margin, crosstalk or echoes. The lowest net loss at which a circuit equipped with repeaters may be operated without passing the limiting requirements for any of these characteristics is called the minimum net loss of the circuit. Since it is desirable to keep the net loss of a circuit at any time at least as great as the minimum net loss, an allowance for the probable circuit variations is added to the minimum net loss to obtain the minimum working net loss. This minimum working net loss is in general not directly proportional to the length of the circuit although in some cases within the important range of distances it can be considered to be proportional to a sufficient degree of accuracy.

It is evident that the minimum working net loss is a characteristic of fundamental importance in the design of new toll cables as well as in determining the operating limitations of existing cable circuits. Circuits having the same type of loading and the same spacing of repeaters may have widely different minimum net losses. This can come about because of differences in the accuracy with which crosstalk coupling is reduced in the manufacture and installation of the cable and its associated loading coils and apparatus, differences in the degree of uniformity of these characteristics and differences in the perfection of balance and matching of impedance between the cable conductors and the associated equipment. In the United States the study of the crosstalk, impedance and echo results obtained in various toll cables has led to the development of standard practices as to

uniformity of construction and detailed specifications of the equipment with which the minimum net loss to be obtained with new toll cables can be closely predicted.

Performance Characteristics of Two-Wire Circuits

Fig. 3 shows, for B and H-88-50 two-wire circuits used exclusively for terminating business, the minimum working net losses for various distances as limited separately by crosstalk, echoes and singing. Of course, the lower the net loss the greater is the tendency toward excessive echoes, crosstalk or possibility of singing. For any given case the most exacting limitation controls the minimum working net loss.

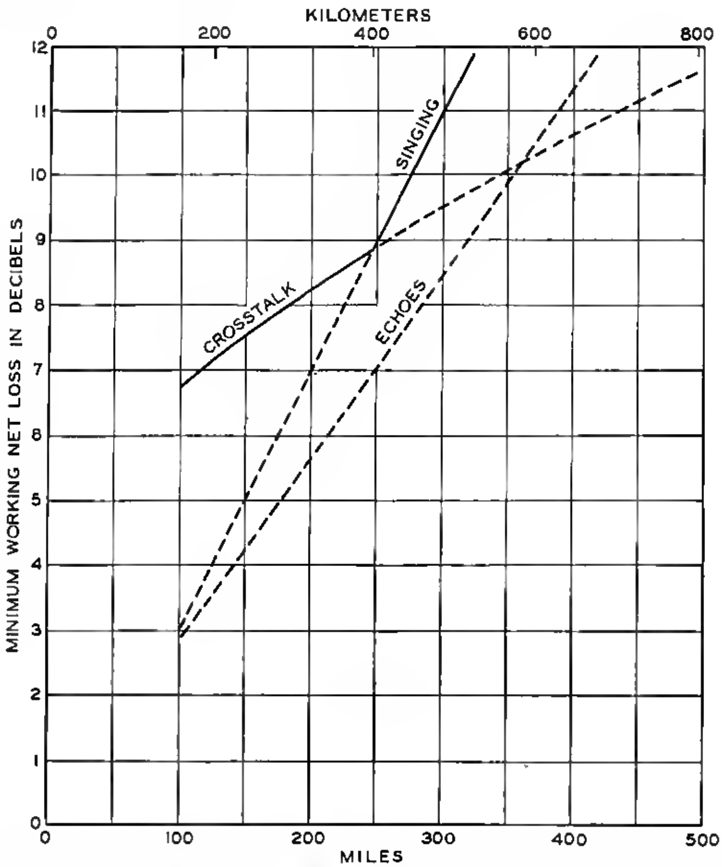

Fig. 3—Minimum working net loss of 19-ga. B and H-88-50 two-wire facilities versus circuit length for terminating business. These apply to either 50-mile (80 km.) sections of B-88-50 or 45-mile (72 km.) sections of H-88-50, whichever has the more severe limitations.

These curves include allowance for the unavoidable variations in the net loss which occur from time to time due to repeater battery variations, residual variations left over after pilot wire regulators have removed major transmission variations due to temperature changes in the cables, humidity effects in office wiring, etc.

Performance Characteristics of Four-Wire Circuits

Fig. 4 shows, for four-wire circuits used exclusively for terminating business, the minimum working net losses for various distances as limited separately by crosstalk and echoes. The possibility of singing does not enter as a limitation on these circuits. In these curves suitable allowance has also been made for the effect of the unavoidable transmission variations.

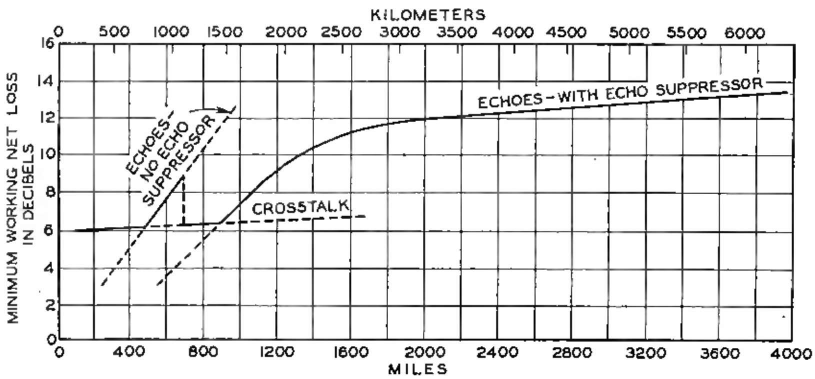

Fig. 4—Minimum working net loss of 19-ga. H-44-25 four-wire facilities versus circuit length for terminating business.

It will be observed that crosstalk is controlling only for the shorter distances up to a little over 400 miles (640 kilometers). Up to this length meeting proper crosstalk limits requires that the net loss be kept above about 6 db.

Echo constitutes the important limitation to the net loss of four-wire circuits. As is well known, echo suppressors go a long way toward eliminating echo effects but do not remove these effects, which remain the most important limiting factor on the longer circuits.

Transmission Requirements

The transmission requirements established for toll circuits are based on the provision of adequate transmission for the complete connection between any two points in the United States and the southern part of Canada, and also between any point of the country and the terminals

of the intercontinental circuits. In order that this may be accomplished in an economical and orderly way a general toll switching plan has been adopted for the entire continental area. This plan establishes a fundamental basis for the routing of connections involving more than one toll circuit through the establishment of about 150 important switching centers to which all of the 2500 toll centers of the country will be directly connected. These 150 switching centers are interconnected by groups of high grade toll circuits either directly or for distant parts of the country through the intermediary of "regional centers" of which there are eight in the continental area.

By means of this plan it is possible to allocate each group of toll circuits to one of several broad classifications depending upon its position in the general toll switching plan, and to apply standard transmission requirements to each such broad classification. These requirements include the requirement that the effective net loss of all direct circuits shall not exceed 9 db, and that circuits designed for use in switched connections shall have minimum working net losses not exceeding 3 db for end links, 4 db for circuits between regional centers and 3.5 to 4 db for the remaining intermediate links interconnecting the important switching centers. When several circuits are connected together to form a long switched connection, the overall crosstalk effects are not appreciably increased over the effects of an individual circuit. Singing effects will usually not be limiting since long switched connections are seldom established without at least one intervening four-wire circuit. On the other hand echo effects increase fairly rapidly even with circuits equipped with echo suppressors and therefore, in selecting facilities which will meet the requirements of minimum working net loss previously specified, the echo effects are generally controlling on long connections. Since these circuits are also used for direct circuit connections, higher net losses, which will be satisfactory from the crosstalk and singing standpoints in the terminating condition, are obtained by adding pads at one or both terminals of the circuit for this condition.

A more complete statement of the transmission requirements applied to toll cable circuits in the United States is given in Table II. For convenience there are also given in this table the current transmission requirements for international circuits adopted by the C. C. I. In order to make the comparison as nearly as possible on a comparable basis the international circuit requirements of the C. C. I. are compared with the requirements for American toll circuits interconnecting two regional centers, and the requirements for the national terminal are compared with the American requirements for connections from the

TABLE II

Transmission Standards

Bell System	*C. C. I.*
Number of Regional Centers—8	Number of European National Outlets —29
NET LOSS	
Circuits Between Regional Centers (On effective transmission basis)	*International Circuits* (Based on 800-cycle transmission equivalent)
Future Plant	*Future Plant*
Terminating Business: 9.0 db Switched Business (Via Net Loss)*: 3.0 db	Terminating or Switched Business Two-Wire....... 8.7 db Four-Wire....... 6.9 db
Existing Plant	*Existing Plant*
Terminating Business: 9.0–11.0 Switched Business: 3.0–5.0 db	Two-Wire.......11.3 db Four-Wire....... 9.6 db
MAXIMUM OVERALL NET LOSS BETWEEN SUBSCRIBERS†	
Regional Center Transmitting Loss.................... 16 db Regional Center Receiving Loss 12 db Circuit Between Regional Centers (Via Net Loss)........ 3–5 db Total..................31–33 db	National Transmitting Loss... 17 db National Receiving Loss...... 11 db International Circuit......... 7–11 db Total...................35–39 db
FREQUENCY BAND WIDTH	
250 to 2750 cycles Loss at extreme frequencies 10 db greater than at 1000 cycles. For narrower bands the effective transmission equivalent reflects the effect on transmission of band width.	300 to 2400 cycles Loss at extreme frequencies 8.7 db greater than at 800 cycles.
DELAY DISTORTION	
Direct circuit connection (terminal circuit)—20 milliseconds. Via circuits (in switched connections) 10 milliseconds. (Differences between 1000 cycle delay and the highest frequency effectively transmitted.)	*Overall Connection* 30 milliseconds as the difference between the time of propagation for the highest frequency effectively transmitted and the time of propagation for 800 cycles.
NON-LINEAR DISTORTION	
No fixed limits at present on message circuits but consideration is being given to methods of measuring and evaluating the impairment due to this effect.	No fixed limits at present on message circuits but consideration is being given to methods of measuring and evaluating the impairment due to this effect.

* Via net loss is the loss which the circuit contributes to an overall connection when switched to toll lines at both ends.

† The regional center and national outlet transmitting and receiving losses are the maximum losses between the most distant subscriber in the particular area served by the regional center or national outlet and the particular regional center or national outlet.

TABLE II—(*Continued*)

Bell System	C. C. I.
TRANSMISSION VARIATIONS (AVERAGE OF THE TWO DIRECTIONS)	
250-mile (400-kilometer) circuits ± 1.5 db, 1000-mile (1600-kilometer) circuits ± 3.0 db (these limits are exceeded approximately 5 per cent of the time).	No limits.
ECHOES	
Echoes are limiting in accordance with curves representing the results of experience as to permissible loudness of echo without interference for different times of propagation. See page 129 of the "Red Book" of the C. C. I. On four-wire circuits echo suppressors are employed for all circuits used for switched business in excess of 270 miles (430 kilometers) of H-44-25 facilities. Four-wire circuits used for terminal business only are equipped with echo suppressors when they exceed approximately 650 miles (1000 kilometers) of H-44-25 facilities. Echoes on circuits so equipped are limiting as indicated in Fig. 4 of this paper.	Echoes are limiting in accordance with curves representing the results of experience as to permissible loudness of echo without interference for different times of propagation. See page 129 of the "Red Book" of the C. C. I.
SINGING MARGIN (TERMINAL CONDITION)	
10 db for two and four-wire circuits.	Two-wire 6.8 db. Four-wire 9.0 db.
CROSSTALK	
For quiet circuits: Average—70 db. Maximum—60 db. (Based on 1 per cent chance of exceeding 60 db.)	54 db at least.
MINIMUM WORKING NET LOSS*	
4 db.	No limits established.
TIME OF PROPAGATION	
For continental communication—250 milliseconds. Continental circuits in an intercontinental connection—100 milliseconds. For continental communication: Delay between echo suppressors—100 milliseconds.	For continental communication—250 milliseconds. Continental circuits in an intercontinental connection—100 milliseconds. For continental communication: Delay between echo suppressors—100 milliseconds.
NOISE (INCLUDING BABBLE) **TERMINAL CONDITION MEASURED AT THE TOLL SWITCHBOARD**	
+ 26 db (200 noise units) referred to reference noise (approximately 10 noise units). For noise values greater than above limit N. T. I.'s are applied.	*2 Millivolts (Approximately 160 Noise Units)* (Equivalent intensity of 800-cycle tone of the limiting voltage across a receiver whose impedance is adjusted to 600 ohms.)

* For more detailed discussion refer to text.

subscriber to a regional center. As there are eight regional centers in the United States and 29 national networks which constitute the European continental network, the areas involved in the comparison are not wholly comparable.

The application of these transmission requirements leads to the following approximate limits for the use of the different standard types of toll cable construction in the toll circuits of the United States:

19-gauge B and H-88-50 two-wire circuits	250 miles (400 kilometers) when used exclusively for terminating business
19-gauge B and H-88-50 two-wire circuits	135 miles (220 kilometers) for circuits used for switched business
19-gauge H-44-25 four-wire circuits without echo suppressors	650 miles (1050 kilometers) when used exclusively for terminating business
19-gauge H-44-25 four-wire circuits without echo suppressors	270 miles (430 kilometers) for circuits used for switched business

Use of Toll Cables in the United States

In the application of toll cables to meet the service requirements of the United States use is generally made of cables 2⅝ inches (67 millimeters) in outside diameter, although to some extent use has been made of cables 3⅛ inches (79 millimeters) in outside diameter. A large proportion of the new toll cables contain one of the combinations of gauges indicated in the following table:

TABLE III

	16-Gauge Quads	16-Gauge Pairs	19-Gauge Quads	22-Gauge Quads
Cable 1......	0	6	148	1
Cable 2......	19	6	114	1

The present toll cable routes in the United States are indicated on the map shown in Fig. 5, together with probable future extensions. The existing network includes 13,000 miles (21,000 kilometers) of route, 21,000 miles (34,000 kilometers) of cable, and when fully equipped, 5,000,000 miles (8,000,000 kilometers) of circuit.

The division of the cable between various types of construction is indicated in the following table:

Underground in ducts	46%
Aerial	50%
Buried underground	4%

As an illustration of the practical application of toll cable, some information is given below regarding the makeup of some of the circuits out of New York City. There are associated with the New York toll board 235 groups of circuits. In order to avoid too cumber-

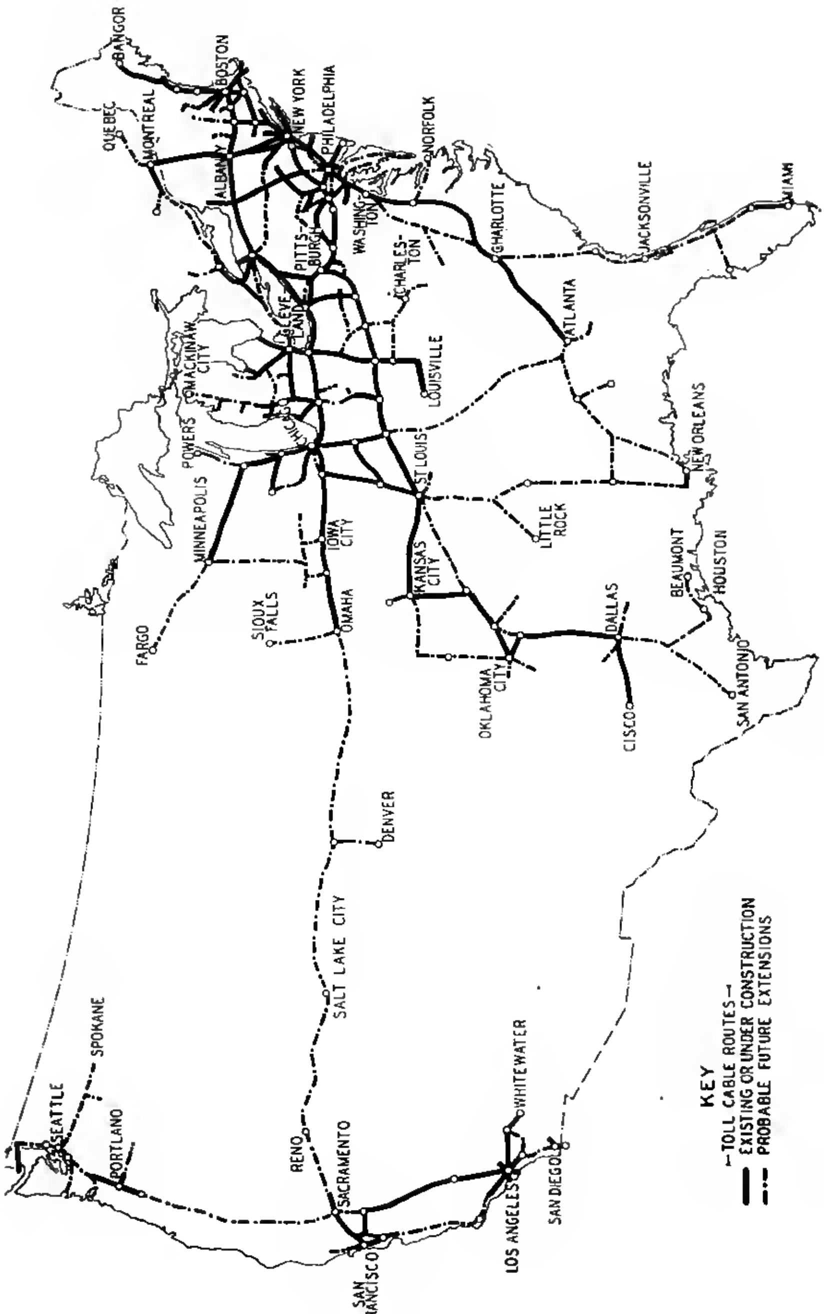

Fig. 5—Toll cable routes—Bell System.

some an illustration, we shall consider only circuits from New York to other regional centers and primary outlets. Chicago has a larger number of connections to these points but New York is chosen because of its interest in connection with international service. These circuits are indicated on the map in Fig. 6.

Of the 64 circuit groups to regional centers and primary outlets, 43 are less than 870 miles (1400 kilometers) in length, 95 per cent of the circuit mileage being cable. The makeup of a few of these groups chosen for the purpose of illustration is given in Table IV.

The remaining circuit groups indicated in Fig. 6, 870 miles (1400 kilometers) and more in length, and 21 in number, have the makeups and electrical characteristics indicated in Table V.

It will be noted that the average circuit in this classification is made up of about one half four-wire toll cable circuit and the other half of carrier telephone superimposed upon open wire. Since carrier circuits have, in general, electrical characteristics comparable to the four-wire cable circuits and have a relatively high velocity of propagation, the combination of four-wire with carrier results in very satisfactory electrical characteristics, even for the longest circuits.

A point of interest in connection with the table is the time of propagation. This is, in all cases, well within the provisional limit of 100 milliseconds adopted by the C. C. I. for the time of propagation of the continental terminating circuits of an intercontinental connection.

Future Requirements of Very Long Cable Circuits

At the present time cable up to lengths of 1800 miles (3000 kilometers) is used in the regular routine in the United States and gives a satisfactory performance. Tests have been made on longer four-wire cable circuits up to lengths exceeding 3600 miles (6000 kilometers). These tests show that for such lengths, and particularly for the much greater lengths which may result from the development of intercontinental telephone service, the present design of toll cable circuits would not be entirely satisfactory.

More Effective Echo Suppressors

Circuits 3600 miles (6000 kilometers) long when equipped with ordinary echo suppressors fail to give the net loss of 9 db which has been set up as a design objective. A more effective type of echo suppressor is necessary to work such a circuit at as low a net loss as 9 db. Experiments have been made with an echo suppressor of a type which changes its sensitivity automatically, depending upon the

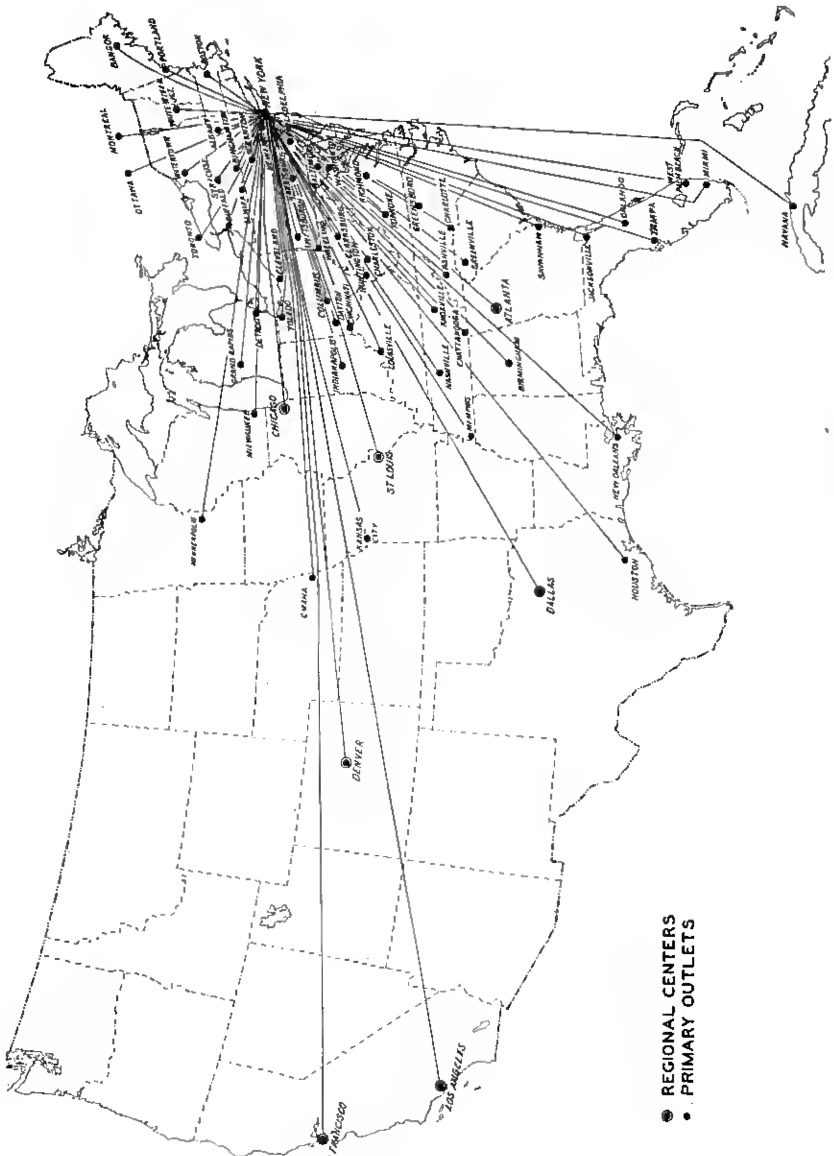

Fig. 6—Direct circuit groups from New York to regional centers and primary outlets.

TABLE IV

TYPICAL CIRCUITS FROM NEW YORK TO REGIONAL CENTERS AND PRIMARY OUTLETS LESS THAN 870 MILES (1400 KILOMETERS)—JANUARY 1932

City	Class*	Number of Circuits	Length		Make-Up	Effective Net Loss—db	
			Kilometers	Miles		Terminal Condition	Via Condition
Philadelphia	Via	24	140	87	Four Wire H-44-25	6	0
	Term	299			Two Wire Older Types of Loading	12†	—
Boston	Via	17	367	228	Four Wire H-44-25	9	3
	Term	85			Two Wire Older Types of Loading	12†	—
Washington	Via	7	359	223	Four Wire H-44-25	8	2
	Term	44			Four Wire H-44-25	8	—
Pittsburgh	Via	15	587	365	Four Wire H-44-25	8	2
	Term	24			Two Wire H-44-25	8	—
Baltimore	Via	6	299	186	Four Wire H-44-25	8	2
	Term	32			Four Wire H-44-25	8	—
Albany	Via	12	249	155	Two Wire H-44-25	8	2
	Term	23			Two Wire H-172-63	12†	—
Cleveland	Via	8	817	507	Four Wire H-44-25	9	3
	Term	18			Four Wire Older Type Loading	13†	—
Detroit	Via	9	1,090	677	Four Wire H-44-25	9	3
	Term	17			Four Wire Older Type Loading	12†	—
Toronto	Via	7	803	499	Four Wire H-44-25	9	3
	Term	9			Two Wire H-172-63	11†	—

* Via—Circuits used for switched business.
Term—Circuits used for terminal business only.

† With further growth of plant these circuits will be brought within present limits by reloading or by replacing with new circuits, limiting the older types of loading to shorter distances.

TABLE V

DIRECT CIRCUIT GROUPS FROM NEW YORK TO REGIONAL CENTERS AND PRIMARY OUTLETS EXCLUDING THOSE LESS THAN 870 MILES (1400 KILOMETERS)—JANUARY 1932

City	Number of Circuits	Circuit Make-Up								Effective Net Loss db		1000-Cycle Delay Milliseconds
		Kilometers				Miles						
		Four Wire H-44-25	Type C Carrier	Other	Total	Four Wire H-44-25	Type C Carrier	Other	Total	Terminal Condition	Via Condition	
Atlanta	9	1,010	606	—	1,616	623	380	—	1,003	9	3	36
Birmingham	3	1,010	843	—	1,853	623	527	—	1,150	9	3	37
Chicago	59 *	1,400	—	—	1,400	—	—	—	—	9	3	46
Dallas	4	1,605	1,084	—	2,689	998	673	—	1,671	10	4	58
Denver	3	1,685	1,465	—	3,150	1,048	910	—	1,958	10	4	61
Havana	3	359	2,300	—	2,659	221	1,430	—	1,651	10	4	22
Houston	3	1,605	1,210	—	2,815	998	751	—	1,749	10	4	58
Jacksonville	8	1,010	—	632	1,642	623	—	398	1,021	9	3	37
Kansas City	5	2,010	—	—	2,010	1,250	—	—	1,250	10	4	67
Los Angeles	7	1,485	4,110	—	5,595	922	2,554	—	3,476	11	5	66
Memphis	3	1,100	863	—	1,960	684	534	—	1,218	9	3	40
Miami	19	1,010	1,215	—	2,225	622	759	—	1,382	9	3	38
Minneapolis	5	1,685	647	—	2,332	1,048	401	—	1,449	9	3	39
New Orleans	7	1,010	1,425	—	2,435	623	890	—	1,513	9	3	39
Omaha	2	2,175	—	—	2,175	1,350	—	—	1,350	10	4	72
Orlando	3	1,010	—	900	1,910	623	—	559	1,182	10	4	39
St. Louis	13	1,605	—	—	1,605	998	—	—	998	9	3	53
San Francisco	6	1,830	3,430	—	5,260	1,137	2,133	—	3,270	11	5	75
Tampa	5	1,010	931	—	1,941	623	585	—	1,208	9	5	37
Tulsa	2	1,605	703	—	2,308	998	438	—	1,436	10	4	56
West Palm Beach	9	1,010	1,105	—	2,115	623	690	—	1,313	9	3	38

* 45 Circuits for Terminal Business Only.
Note: All of these circuits are equipped with echo suppressors.

amount of noise on the circuit at any given time, the less noise the more sensitive the device. It has been found possible to adjust this device to sufficient sensitivity to permit working a 3600-mile (6000-kilometer) circuit with 9 db net loss. When noise is added to the circuit the sensitivity of the device, of course, diminishes but the added echo is largely masked by the increased noise.

Delay Distortion

For a 3600-mile (6000-kilometer) H-44-25 circuit the difference in the delay at 1000 cycles and at 3000 cycles amounts to about 0.025 second. Experiments which have been made on circuits introducing very little non-linear distortion indicate that this amount of delay distortion by itself is not particularly serious. However, on the long four-wire circuits where non-linear distortion is also present, the effect of delay distortion becomes more pronounced so that it becomes quite objectionable. Delay distortion correctors would therefore be required for H-44-25 circuits of this length, although for circuits of 1800 miles (3000 kilometers) they do not appear necessary.

Time of Propagation

When a long connection is built up using cable circuits, the delay proper, quite apart from delay distortion, becomes important. For a 3600-mile (6000-kilometer) length of H-44-25 circuit equipped with delay equalizers the time of propagation is about one-quarter of a second in each direction. This time of propagation is generally considered about all that should be tolerated and is the C. C. I. tentative limit for a complete connection.

Adverse Interaction of Two Echo Suppressors

When voice-operated devices are introduced on very long cable circuits another complication results. Assume, for example, that the 3600-mile (6000-kilometer) connection is made up of two links, each equipped with an echo suppressor of the usual type, either mechanical relay or vacuum tube operated. Assume that the echo suppressors are 1800 miles (3000 kilometers) apart, the delay between these devices being one-eighth of a second for each direction of transmission. When conversations are carried on over this circuit it is found that occasionally when the speakers at the two ends utter words at nearly the same instant both echo suppressors respond, each echo suppressor blocking one direction of the circuit. Consequently, certain words or parts of words are lost. In telephone conversations it is found that with such a circuit arrangement if the time of propagation in each direction between echo suppressors does not exceed about 0.1 second,

the amount lost apparently is not a serious handicap. The C. C. I. has tentatively recommended that 0.1 second be taken as a limit towards which it is desirable to work if practicable.

Better Cable Circuits Desirable for Extreme Distances

These difficulties with the present type of cable construction all become more pronounced if, instead of a 3600-mile (6000-kilometer) circuit, consideration is given, for example, to possible future intercontinental circuits in all cable construction. Such a circuit between San Francisco and Istanbul, for example, would be about 10,000 miles (16,000 kilometers). The time of propagation for such a connection would be about .6 of a second in each direction so that two-way conversations would be seriously impeded. Serious difficulties would also be experienced with the voice-operated devices and because of the accumulated distortions, including non-linear effects. While, therefore, it is possible that a circuit of this sort could be used for two-way telephony between Istanbul and San Francisco, the imperfections of such a circuit would be so outstanding as to warrant a serious effort to develop something better if this could be done at a reasonable cost.

Telephone Carrier in Cable

In order to obtain better transmission results over very long cable circuits in an economical manner the development of a carrier system for cables has been actively undertaken. The development work of the Bell System has now been carried to the point where it seems assured that it will be successful and that telephone carrier will have an important field of use in long distance cables on heavy routes.

This carrier system uses non-loaded cable conductors whose velocity is very high as compared to voice-frequency loaded circuits, the effective circuit velocity including delays introduced by apparatus being about 100,000 miles (160,000 kilometers) per second. An experimental trial system has been set up by looping circuits back and forth in a cable so as to produce the equivalent of the system shown in Fig. 7. It will, of course, be understood that this figure represents merely the experimental setup and should therefore not be considered the ultimate in such matters as carrier channels per pair, repeater spacing, etc.

Talking tests which were made using this experimental setup showed very satisfactory quality of transmission and no appreciable interference between circuits In addition to testing each of the nine telephone circuits shown in the sketch, these nine circuits were con-

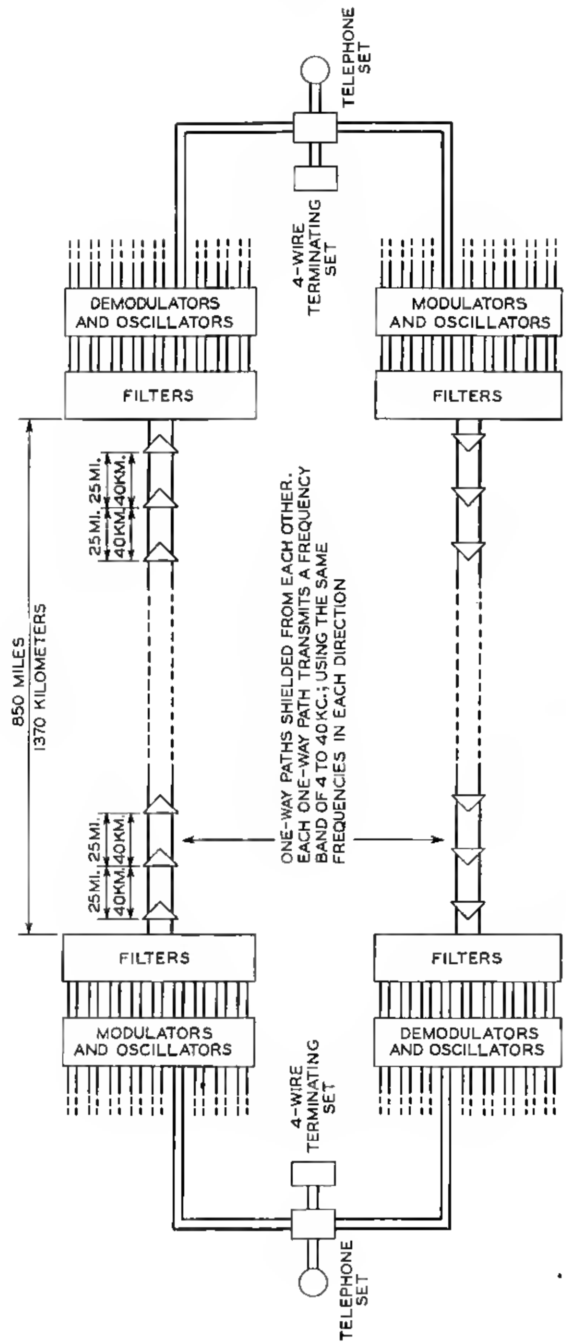

Fig. 7—Experimental cable carrier telephone circuit.

nected in tandem giving an overall length of 7500 miles (12,000 kilometers) of circuit. Conversations over this 7500-mile (12,000-kilometer) circuit were very satisfactory. In fact, the transmission quality was not greatly impaired even when a 15,000-mile (24,000-kilometer) length of one-way circuit was established by connecting all of the links in tandem.

While the development of this carrier system is far from completion and it is not clear at the present time how far it can be applied to other than heavy traffic routes, it is certain that wherever this form of construction is justified, distance no longer remains as a limiting factor.

In the fifty years since the first International Electrical Congress at Paris, the new art of telephone communication has passed through many stages of development and during the past thirty years a new art, making possible communication in cable over long distance, has been born and brought to maturity. This has been made possible by a number of important and fundamental developments such as loading, quadded cable and telephone repeaters. While the development has been rapid, particularly during the past twenty years, it is not too much to expect that the next twenty or thirty years will witness an even greater and more rapid technical development and expansion in the use of long distance toll cables in all parts of the world, associated with a continued increase in the service rendered to mankind by long distance telephone communication.

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